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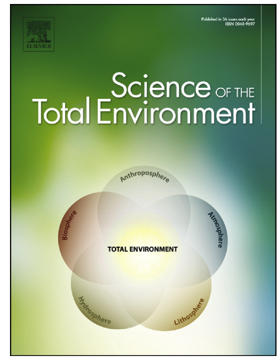
Published in:
Science of the Total Environment

DOI:
10.1016/j.scitotenv.2019.01.399

Publication date:
2019

Citation for published version (APA):
Lisenby, P. E., Tooth, S., & Ralph, T. J. (2019). Product vs. process? The role of geomorphology in wetland characterization. *Science of the Total Environment*, *663*, 980-991. https://doi.org/10.1016/j.scitotenv.2019.01.399

Accepted Manuscript



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PII: S0048-9697(19)30446-2
DOI: https://doi.org/10.1016/j.scitotenv.2019.01.399
Reference: STOTEN 30713

To appear in: *Science of the Total Environment*

Received date: 16 October 2018
Revised date: 30 January 2019
Accepted date: 30 January 2019

Please cite this article as: P.E. Lisenby, S. Tooth and T.J. Ralph, Product vs. process? The role of geomorphology in wetland characterization, Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2019.01.399

Product vs. Process? The Role of Geomorphology in Wetland Characterization

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Highlights

- Hydrogeomorphic wetland classification schemes fail to recognize landform dynamism
- Geomorphological processes determine the capacity for wetland landform adjustment
- Sediment connectivity and landform sensitivity control wetland landform adjustment
- Wetland landform adjustment is a key control on ecosystem service delivery
- Wetland classification should incorporate process geomorphology to aid management

Abstract

Wetland classification has become a primary tool to characterize and inventory wetland landscapes, but wetlands are difficult to classify because they straddle the terrestrial and aquatic boundary and occur in a variety of hydroclimatic and topographic settings. Presently, many ecological wetland classification schemes are focused on the 'hydrogeomorphic' unit, which attempts to account for the physical setting of a wetland. In many cases topographic terms (e.g. flats, slopes) rather than geomorphological terms (e.g. oxbow, floodplain) are used to characterize landforms, and little attempt is made to characterize the process-landform relationships within wetland landscapes. The current misrepresentation of product geomorphology (i.e. topographic rather than landform description) and underrepresentation of process geomorphology (i.e. lacking process-landform relationships) means that many current wetland classification schemes represent an incomplete and static attempt to characterize geomorphologically dynamic wetland landscapes. Here, we use examples from wetlands in the drylands of Africa, Australia, and North America to identify the capacity for adjustment (i.e. form and timescale of adjustment) of wetland landforms and we relate this capacity to the geomorphological concepts of sediment connectivity and landform sensitivity. We highlight how geomorphological insights into process-landform relationships and timescales of landform adjustment can add value to wetland classification efforts, with important implications for wetland management and ecosystem service delivery. We submit that geomorphology has a much larger role to play in wetland characterization and can enhance existing wetland classification schemes. More participation by the geomorphology community in wetland science and more awareness by the ecology community in recognizing and characterizing wetlands as dynamic landscapes will facilitate more effective wetland research and management.

Keywords: ecosystem services, geomorphological adjustment, landform sensitivity, sediment connectivity, wetland management

1. Introduction

Wetlands are a premier example of how the atmosphere, lithosphere, biosphere, and hydrosphere integrate to produce a natural environment that increasingly intersects with the anthroposphere (Mitsch and Gosselink, 2015). Wetlands provide vital landscapes for human livelihoods and well-being (Millennium Ecosystem Assessment, 2005c; Junk et al., 2013), yet continue to undergo widespread degradation and/or loss due to biophysical decline resulting from anthropogenic modification and other environmental pressures (Gardner et al., 2015; Reis et al., 2017; Ramsar Convention on Wetlands, 2018). Considerable efforts have been made to identify and classify different wetland types as a basis for wetland conservation, management, and ecosystem service inventories (Finlayson and van der Valk, 1995; Sieben et al., 2011, 2018; Junk et al., 2013). Many wetlands remain difficult to characterize and classify, however, because they: 1) straddle the terrestrial-aquatic boundary; 2) have seasonal, intermittent, or ephemeral hydrological regimes; and 3) occur in various topographic settings (e.g. hillslopes through valley bottoms) (Scott and Jones, 1995). Wetlands in drylands (WiDs) – a collective term that includes shallow lakes, floodplains, marshes, swamps, pans, and oases that occur in subhumid through hyperarid environments (The Wetlands in Drylands Research Network, 2014; Tooth et al., 2015b) – exemplify this classificatory conundrum, not only because they occur across various topographies, but also because they encompass a variety of biophysical forms and are found in diverse and often marginal hydro-climatic settings (Williams, 2000; Millennium Ecosystem Assessment, 2005b). While some WiDs support permanent surface water or saturated soils, many are wetted only temporarily following irregular heavy rainfall-runoff events before undergoing prolonged drying, yielding 'boom and bust' cycles (Leigh et al., 2010). Where dry states are the 'norm', such wetlands tend to be poorly recognized and thus excluded from many biological, ecological, and hydrological classification approaches (Stevens et al., 2008; Schael et al., 2015; Marshall et al., 2018). Nonetheless, these otherwise water-deficient drylands may take on a disproportionate importance for many aspects of ecosystem service delivery (Millennium Ecosystem Assessment, 2005b; c). This underscores the need for more robust approaches to wetland characterization that take account of the variable, dynamic nature of many drylands and their constituent wetland landscapes.

Wetland classification schemes tend to be dominated by biological, ecological, and/or hydrological perspectives, with only a cursory reference to wetland geomorphology (Tooth and McCarthy, 2007). For example, the hydrogeomorphic (HGM) wetland classification system is one of the most widely implemented approaches for classifying wetlands (Sieben et al., 2018). Despite the name, the application of geomorphology in HGM schemes is largely restricted to identifying the 'topographic location within the surrounding landscape' (USDA, 2008, p. 2) (cf. Brinson, 1993; Smith et al., 1995), with an HGM unit defined as an area of homogeneous or uniform geomorphological and hydrological conditions (cf. Maltby and Acreman, 2011; Sieben et al., 2011). Consequently, in many cases the application of geomorphology is being misrepresented to serve as an identification method for topographic setting (e.g. flats, slopes) rather than specific landforms (e.g. oxbow, floodplain). This suggests that while geomorphology is recognized as an important factor in wetland distribution (Curie et al., 2007; Uzarski et al., 2017), other variables (e.g. surface hydrology) are typically considered to be more important for wetland development (e.g. Dong et al., 2016). Therefore, the emphasis on 'product' geomorphology (topography/landform) over 'process' geomorphology (process-landform relationships) in wetland classification engenders the assumption that wetlands have a static physical template upon which biological, ecological, and hydrological processes interact. This is especially problematic because many wetlands are influenced by fluvial processes and therefore constitute part of the river (dis)continuum, i.e. controlling longitudinal, lateral, and vertical distributions of water, sediment, and nutrients and acting as unique structural elements within river networks (cf. Poole, 2002; Phillips, 2007; 2015).

These issues leave a significant knowledge gap surrounding the influence of wetland erosion, sedimentation, and associated landform dynamics (e.g. lateral channel migration, floodplain aggradation, tributary fan progradation, gully incision) on wetland structure, function, and ecosystem service delivery (Tooth et al., 2015a). Some research has highlighted the role of process geomorphology in understanding wetland distribution and change; for instance, in mangrove swamps (Balke and Friess, 2016), temperate upland swamps (Cowley et al., 2016), ciénegas (Heffernan, 2008), and lowland floodplain wetlands in Australia (Ralph et al., 2011) and southern Africa (Tooth and McCarthy, 2007; Larkin et al., 2017a). Moreover, geomorphological insights have contributed to floodplain and wetland management (McCarthy et al., 2010; Ralph et al., 2016). Belatedly, some recognition has also been given to the importance of interactions between ecology, sediment flux, and water movement ('biogeomorphology') (cf. Phillips, 1995) in wetland landform/landscape change (Tooth and McCarthy, 2004; Rogers et al., 2010). Nevertheless, our contention is that this research represents the exception, rather than the rule. We suggest that this situation reflects the inadequate integration of geomorphology with biology, ecology, and hydrology in wetland research, whether due to a lack of participation by the geomorphology community or a lack of awareness by the biological, ecological, and hydrological communities. This severely limits our understanding of process-landform relationships which can provide vital components of wetland classification schemes.

In this discussion article, we highlight the importance of geomorphology in wetland characterization by demonstrating the inextricable relationship between wetland landform assemblage and geomorphological processes of landform adjustment. We use existing geomorphological research from WiDs in southern Africa, southeastern Australia, and the American Southwest to: 1) identify the capacity for geomorphological adjustment (i.e. form and timescale of adjustment) of characteristic wetland landforms; 2) illustrate how geomorphological concepts (e.g. sediment connectivity and landform sensitivity) can be used to contextualize and explain these landform adjustments; 3) outline how process geomorphology can enhance existing wetland classification schemes; and 4) discuss how geomorphological process-product insights can aid wetland management strategies and assessments of ecosystem service delivery.

2. Capacity for Geomorphological Adjustment in WiDs

To demonstrate the capacity for geomorphological adjustment, we have selected a range of well-documented WiDs in South Africa (Tshwane River, Klip River, Blood River), Botswana (Okavango Delta), southeastern Australia (Macquarie Marshes, Gwydir River, Lachlan River), and the American Southwest (various ciénegas). These wetlands are all associated with river channels and represent some of the larger and more geomorphologically dynamic WiDs. Table 1 provides descriptions of the geomorphological process and landform terms used in our wetland characterizations. We do not consider the different adjustments exhibited by shallow dryland lakes, pans, oases, isolated depressions, or slope seeps, which are usually not dominated by riverine processes but rather by groundwater exfiltration, biogeochemical processes such as salt precipitation and other forms of chemical sedimentation, or by aeolian processes such as deflation.

Northeastern South Africa: The Tshwane, Klip, and Blood River Wetlands

The Tshwane, Klip, and Blood rivers are located on the South African Highveld and are associated with floodplain wetlands up to ~50 km^2 that are inundated during the summer wet season (November through March) and desiccate during the long winter dry season (Tooth et al., 2002; Tooth et al., 2014; Larkin et al., 2017a). The capacity for adjustment varies significantly between the three rivers (Figures 1A, B, C, 2), both in terms of forms and timescales.

Along the meandering lower Tshwane and upper Klip rivers, the primary forms of geomorphological adjustment are lateral migration, aggradation, and avulsion, resulting in a similar suite of channel (e.g. point bars, cut banks) and floodplain landforms (e.g. scroll bars, oxbows, backswamps, paleochannels) (Figures 1A, 2). Timescales of adjustment along the two rivers vary significantly, however, owing to the different hydroclimatic settings. Along the Tshwane River, located in a semiarid setting (Larkin et al., 2017a), discharge and stream power decrease downstream so that the lower reaches are transport limited (i.e. unable to evacuate all the sediment supplied from upstream). Along this laterally migrating, sinuous river (Figure 2), aggradation occurs in and around the channel, elevating the channel ~ 1-2 m above the adjacent floodplain. Channel aggradation reduces channel area and displaces more floodwater overbank, leading to inundation and slow aggradation of floodplain landforms. By contrast, along the upper Klip River, located in a more subhumid setting (Larkin et al., 2017a), discharge and stream power exhibit a slight overall downstream increase, so these reaches are less transport limited. Here, lateral migration rates are relatively slow (Figure 2) and channel elevation is less pronounced (Tooth et al., 2002, 2004). Despite these differences, on both rivers, lateral migration and aggradation interact to promote channel avulsions through an incisional mechanism. During flood flow recession, overbank floodwaters drain back into the channels through local gaps in channel levees, locally inducing gully incision on the channel banks. During subsequent floods, these gullies gradually propagate upvalley through headcut erosion, forming newer, straighter channels that eventually reconnect with the main sinuous channels upstream. These newer channels, being lower in elevation and steeper in slope than the main channels, represent more efficient flow pathways, and as they divert an increasing proportion of flow away from the main channel, lateral migration starts to occur. As a result of waning flows, the original main channel undergoes aggradation and is eventually abandoned to form a paleochannel (Tooth et al., 2007; Larkin et al., 2017b). While these incisional avulsion processes are similar on both rivers, the positive relationship between vertical aggradation rate and avulsion means that avulsions occur far more frequently along the transport-limited lower Tshwane River (Figure 2) (Tooth et al., 2007; Larkin et al., 2017b).

Along the Tshwane and Klip rivers, lateral migration, aggradation, and avulsion have remained the dominant forms of geomorphological adjustment over late Holocene and longer timescales (Tooth et al., 2007; 2009; Larkin et al., 2017b). By contrast, along the upper Blood River, the capacity for adjustment has changed significantly in recent time. Prior to ~100 years ago, the Blood River wetlands were also characterized by a continuous, meandering channel (Tooth et al., 2014). At some point subsequently, possibly during the major 1930s drought, discharge and sediment transport capacity decreased dramatically. The Blood River was unable to maintain a continuous channel (Tooth et al., 2014), leading to channel breakdown and the development of two distinct floodouts (cf. Tooth, 1999; 2004) (Figure 1C), characterized in these wetlands by extensive reedbeds. On these floodouts, clastic and organic sediment aggradation has largely buried the older, now abandoned channel and floodplain landforms, with only short, discontinuous sections of channel now extant. As the floodouts have aggraded, however, slope increases at their downstream ends have promoted incision by gullies, some of which are slowly extending through headward erosion (Tooth et al., 2014) (Figures 1C, 2). Currently the Blood River is associated with both floodplain and floodout zone (cf. Tooth, 2004) wetlands, but in time, these gullies may coalesce and incise new channels through the floodouts, reconnecting discontinuous channel sections and thereby re-establishing a single, through-going channel.

Northern Botswana: The Okavango Delta

The Okavango Delta is a >12,000 km^2 wetland complex that forms part of the endorheic drainage of the Kalahari Basin (Figures 1D, E). The location and aerial extent of the Delta is controlled by several faults that are part of the East African Rift System (McCarthy et al., 2002), and the Delta hosts both permanent and seasonal wetlands that are sustained by austral summer rainfall and flooding. The Delta can be separated into two main regions: the Panhandle and the Fan (cf. Tooth and McCarthy, 2004). The primary forms of adjustment are lateral channel migration, aggradation, and avulsion. Characteristic landforms include scroll bars, oxbows, and paleochannels (Figures 1D,E, 2). Collectively, the process-landform interactions in the two regions contribute to the overall structure and functioning of the Okavango Delta.

In the more confined (<12 km wide), lower gradient Panhandle (Figure 1D), the Okavango River is the main conduit for water and sediment. Discharge and stream power undergo an overall downstream decrease, primarily resulting from lateral leakage through the vegetated channel margins, which helps to maintain extensive areas of permanent swamp (McCarthy et al., 1988; Tooth and McCarthy, 2004). The primary form of geomorphological adjustment is relatively slow lateral migration (Figure 2) (Tooth and McCarthy, 2004) but in some reaches, channel bed aggradation occurs, raising local water levels and driving contemporaneous peat accumulation along the channel margins. Gradually, this suite of processes forms channels that are elevated above the adjacent swamps (Ellery et al., 1993). This further promotes lateral flow dispersal, with flows commonly exploiting pre-existing pathways through swamp vegetation e.g. as created by hippopotami and other animal movements (McCarthy et al., 1992; 1998). These flows tend to be sediment deficient and commonly enlarge the pathways, incising new channels that extend headward toward the elevated channels. The favorable hydraulic gradients along these newly forming channels mean that they capture an increasing volume of flow, resulting in a characteristic anastomosing (multiple-channel) pattern over certain reaches (Smith et al., 1997). In this setting, however, anastomosis may only be a transitional pattern. In the decades to centuries following avulsion, the older, elevated channels are gradually abandoned with the bulk of flow and sediment being routed along a single, dominant, commonly meandering channel (McCarthy et al., 1992; Ellery et al., 1993).

In the unconfined, steeper gradient Fan (Figure 1E), the Okavango River splits into several distributary channels. These channels are more laterally stable, with aggradation and avulsion being the primary forms of adjustment through incisional mechanisms similar to the Panhandle (Figures 1, 2) (McCarthy et al., 1992; Tooth and McCarthy, 2004). Local (small scale) avulsions likely occur frequently (e.g. decadally). Across the Fan as a whole, regional (large scale) avulsions occur on 100-200 year timescales, redistributing water and sediment radially (McCarthy, 2013).

Southeastern Australia: The Macquarie Marshes, and the Gwydir and Lachlan River Wetlands

The Macquarie Marshes, and the Gwydir and Lachlan river wetlands are three large, multi-channel floodplain wetland systems in the semiarid region of the Murray-Darling Basin, southeastern Australia that are subject to varying inundation regimes (permanent to ephemeral) (Figures 1F, G, H). All three floodplain wetlands occur in the lower, unconfined alluvial reaches of their rivers: the Macquarie Marshes along the Macquarie River, the Gwydir wetlands along the Gwydir River, and vast wetlands including the Great Cumbung Swamp along the Lachlan River. The primary forms of adjustment include lateral channel migration, aggradation, incision, avulsion, and channel breakdown. Correspondingly, these wetlands contain a range of landforms (e.g. channels, floodouts, shallow lakes, paleochannels).

In the Macquarie Marshes (Figure 1F), the Macquarie River undergoes a downstream decrease in discharge and stream power (Ralph and Hesse, 2010; Ralph et al., 2016). Lateral migration also decreases downstream, so the primary forms of geomorphological adjustment are aggradation, avulsion, channel breakdown, and incision (Figure 2). Local avulsions on decadal to centennial timescales (Figure 2) form new anastomosing and distributary channels, some of which are associated with wetlands. In some distributaries, for instance, vegetation growth reduces flow velocities and traps sediment, thereby inducing aggradation and decreasing channel size. An increasing proportion of flood flows are displaced overbank, creating suites of shallow floodplain marsh channels and with some channels breaking down to form floodouts (Yonge and Hesse, 2009; Ralph and Hesse, 2010; Ralph et al., 2012). In some locations, overbank flows may scour and enlarge floodplain channels and divert an increasing proportion of flood flows, with the older, aggrading distributary channel eventually being abandoned (Oyston et al., 2014). Along the newly scoured floodplain channel, incision can propagate upstream toward the main channel, ultimately leading to an avulsion that redistributes water and sediment to a different part of the floodplain (Yonge and Hesse, 2009; Ralph et al., 2016). This process generates spatial and temporal variability in wetland topographic and ecological development (Yonge and Hesse, 2009; Ralph and Hesse, 2010; Ralph et al., 2011).

Along the Gwydir River (Figure 1G), a downstream decrease in discharge and stream power also drives avulsion, distributary channel and floodout formation, and wetland expansion and contraction (Pietsch and Nanson, 2011), owing to similar processes and feedbacks between flow dispersal, increased roughness due to vegetation, and sedimentation. The Lachlan River also undergoes a downstream decrease in discharge and stream power, leading to a reduction in channel size and the formation of numerous distributary channels (Kemp and Rhodes, 2010) (Figure 1H). Unlike the through-going Macquarie and Gwydir rivers, the Lachlan River eventually terminates in a floodout within the Great Cumbung Swamp (O'Brien and Burne, 1994), probably owing to aggradation and alluvial damming near its confluence with the larger Murrumbidgee River.

The American Southwest: Ciénegas

Ciénegas are wetlands that are located along low-order river valleys, predominantly in New Mexico, Arizona, and parts of northern Mexico (Figures 1I,J) (Hendrickson and Minckley, 1984; Minckley et al., 2013b). These wetlands occur predominantly in association with floodplain and floodout landforms that are locally formed on Pleistocene terraces and paleochannels. Many ciénegas develop where alluvial sediments accumulate in confluence zones or behind structural features (e.g. dikes and sills). Water supply is typically maintained via groundwater flow (springs and seeps) but is commonly supplemented by surface runoff (Sivinski and Tonne, 2011; Minckley et al., 2013a). The primary forms of geomorphological adjustment are aggradation and incision of the channels, floodouts, and/or floodplains (Figure 2). Various Holocene records reveal cyclic phases of aggradation and incision (Minckley and Brunelle, 2007; Minckley et al., 2011), with many ciénegas presently hosting a channel in varied stages of incision or infilling (Hendrickson and Minckley, 1984). Cycles of aggradation and subsequent incision by gullies (regionally termed 'arroyos') are predominantly extrinsically controlled by climate-driven changes in rainfall amount, intensity, and sequencing (Graf, 1988). These climatic influences are manifest through dry/wet cycles, whereby dry conditions yield a drop in water table and reduced vegetation coverage, and subsequent wet periods increase runoff and induce gully formation (Waters and Haynes, 2001; Minckley and Brunelle, 2007). Persistence of wet conditions then promotes increased vegetation growth that stabilizes sediment and induces channel and floodout/floodplain aggradation, aiding wetland development anew (Heffernan, 2008; Heffernan et al., 2008). Cycles of aggradation and incision can also be intrinsically controlled, whereby floodplain/floodout aggradation results in gradient steepening and exceedance of threshold slopes, which then prompts gully formation. Gully formation reduces slope, thereby inducing renewed aggradation (Schumm and Hadley, 1957). Finally, anthropogenic impacts can locally exacerbate gully formation, e.g. through overgrazing and channelization (Graf, 1988; Gellis and Elliott, 2001; Cole and Cole, 2015). In these instances, the natural cycle of aggradation and incision is interrupted and without human intervention, gully headcutting may propagate, unchecked, through the entire length of the ciénega (Antevs, 1952; Hendrickson and Minckley, 1984).

3. Contextualizing Geomorphological Process-Product Relationships

The range of wetland adjustments discussed above establish a specific expectation of geomorphological adjustment (Lisenby and Fryirs, 2016) for each individual wetland landscape over timescales from decades to millennia (Figure 2). Importantly, influences on these adjustments can extend well beyond wetland boundaries, as brought about through the interplay of externally-derived (extrinsic) and internally-derived (intrinsic) controls over a range of spatiotemporal scales (e.g. Larkin et al., 2017a). The geomorphological concepts of sediment connectivity and landform sensitivity encapsulate this interplay and are useful tools with which to derive order from the complexity of geomorphological responses observed in fluvial landscapes (Lisenby et al., 2017). The terms 'connectivity', 'sensitivity', 'resilience', and 'recovery' have been used extensively in the disciplines of biology, ecology, hydrology, and geomorphology, developing numerous definitions (Supplementary Table S1). These definitions are not always compatible within and between disciplines. It is critical that future collaborative work between geomorphologists, biologists, ecologists, and hydrologists begin to reconcile rather than further diversify the existing suite of conceptual terminology. To promote clarity here, we use sediment connectivity to refer to the ease with which sediment can enter and propagate along fluvial transport pathways throughout a landscape (cf. Bracken et al., 2015; Lisenby and Fryirs, 2017). Landform sensitivity is defined narrowly as the ease with which landforms can geomorphologically adjust (cf. Reid and Brierley, 2015; Lisenby and Fryirs, 2016).

Wetlands act as sediment buffers (cf. Fryirs et al., 2007) within the broader landscape by impeding sediment transfer and serving as sediment storage areas (Phillips, 1989; Grenfell et al., 2009; Keen-Zebert et al., 2013; Tooth et al., 2014). Forms of geomorphological adjustment, both within and outside of wetlands, play different roles in terms of how they facilitate sediment connectivity to or through wetlands, laterally or longitudinally. Sediment buffering and storage are achieved through depositional forms of adjustment that produce landforms such as levees and floodplains (Figure 2). These landform adjustments inhibit longitudinal connectivity through wetlands but may encourage lateral sediment connectivity across a wetland through lateral migration and/or avulsion (e.g. the Tshwane, Klip, Okavango, Macquarie Rivers – Figure 1A, B, D, E, F, respectively). Correspondingly, erosional forms of adjustment are essential for facilitating lateral sediment connectivity via lateral migration or channel incision. Conversely, some forms of erosional adjustment facilitate longitudinal sediment connectivity while reducing lateral connectivity (e.g. gully incision of floodouts/ciénegas – Figure 1C, I). While gullying reduces sediment storage capacity, it may still be a natural form of wetland adjustment (e.g. as driven by the crossing of an intrinsic slope threshold). Additionally, changes in sediment connectivity or availability within a wetland via reductions in transport capacity can alter wetland landforms and fundamentally change the capacity for adjustment within a wetland landscape as shown by the marked transformation of the Blood River from a continuous, through-going river to a discontinuous, partly-channeled river with floodouts over the past ~ 100 years (Figure 1C) (Tooth et al., 2014). Importantly, adjustments that operate outside of wetlands can influence wetland sediment (dis)connectivity (cf. Fryirs, 2013) and hydro-geomorphic conditions in riverine environments (e.g. Wethered et al., 2015). For instance, a decrease in upstream sediment connectivity can reduce aggradation rates and/or induce channel incision in downstream wetlands, while upstream increase in sediment connectivity may accelerate aggregation rates and induce more frequent avulsions in downstream wetlands. Downstream, changes to base level may induce knickpoint retreat (base level drop) or further sediment aggradation (base level rise) in upstream wetlands. Future changes in connectivity controls (e.g. resulting from climate or land use changes) is a key consideration for understanding future wetland dynamics (Grenfell et al., 2014; Larkin et al., 2017a; Larkin et al., 2017b), not just in riverine WiDs, but in all WiDs including shallow lakes and pans that rely on sediment and nutrients from a broader catchment.

Sediment connectivity and landform sensitivity are inextricably linked because forms of geomorphological adjustment essentially represent exchanges of sediment (e.g. Harvey, 2001). The wetland landforms discussed here (Figure 2) display varying degrees of sensitivity to a range of geomorphological adjustments. For example, the Tshwane and Okavango Panhandle channels have longitudinal sediment connectivity and can be characterized as sensitive as they are both laterally active and prone to avulsion over decadal to centennial timescales. The Macquarie and Okavango Fan channels have less longitudinal sediment connectivity, but nonetheless are sensitive to channel breakdown, abandonment, and avulsion over similar timescales. Similarly, ciénegas and floodouts are products of decreased longitudinal sediment connectivity but ultimately can become sensitive to gully incision (Figure 2), which would then enhance longitudinal sediment connectivity over decades to centuries.

The foregoing begs a question regarding the difference between landform sensitivity and landscape sensitivity. The floodplain, floodout, and subaerial delta wetlands discussed here all contain sensitive, actively adjusting landforms. This landform sensitivity can both contribute to, and maintain, the development of the wetland (e.g. lateral migration and avulsion) or can locally reduce wetland area and function (e.g. floodout/ciénega incision and gullying). Lateral migration and avulsion incorporate both aggradational and incisional processes and serve to re-distribute sediment, water, and nutrients to rework or create new landforms upon which wetland ecological communities can develop (Kobayashi et al., 2011; Ralph et al., 2011, 2016). Overbank flow connects channeled and unchanneled wetlands that have inherently linked, but spatially distinct, biological and hydrogeomorphic conditions (Kobayashi et al., 2015). A proclivity toward geomorphological adjustment in these wetlands facilitates a dynamic, yet diverse and persistent wetland landscape (cf. Colloff and Baldwin, 2010) with landforms of different age, substrate type, and hydroperiod. Conversely, ciénegas are prone to gully incision which serves to reduce the ecological function of these wetland landscapes (Hendrickson and Minckley, 1984; Cole and Cole, 2015). Importantly, floodout incision can also reconnect a formerly continuous channel, thereby reducing the functionality of one wetland type (floodout) while developing another wetland type (floodplain) (e.g. the Blood River). Therefore, the sensitivity of individual wetland landforms cannot be a direct surrogate for landscape sensitivity in wetlands as a whole (cf. Tooth, 2018). Much like river managers are directed to 'know your catchment' (Brierley et al., 2013), wetland managers must also adopt a landscape perspective to understand how and why wetland landforms may (or may not) change, the spatiotemporal scale of change, and what those changes are related to (e.g. natural or anthropogenic drivers) (cf. Millennium Ecosystem Assessment, 2005a; Phillips, 2018). An essential first step in adopting a landscape perspective is to incorporate knowledge of these geomorphic process-landform relationships into wetland classification schemes.

4. Using Process Geomorphology to Enhance Wetland Classification

All wetland landscapes are formed though geomorphological process, but there is significant variability in the role that these processes play in contemporary wetland dynamics. The WiDs that we have highlighted in this paper (Section 2) rely on suites of fluvial processes to develop over time, as manifest in each wetland through their individualistic capacities for geomorphological adjustment. The spatiotemporal scales of these adjustments are matched to the landforms they create and modify (Figure 2) (de Boer, 1992). Therefore, wetlands are not spatially homogenous, and their landforms are as dynamic as the processes that adjust them. This means that wetland classification schemes that apply geomorphology only to identify topographic setting (e.g. Brinson, 1993; Semeniuk and Semeniuk, 1995; Smith et al., 1995) are simply depicting the wetland as a snapshot in time. In other words, such schemes represent a static attempt to characterize what are commonly dynamic environments (Ellery, 2015).

Geomorphological classifications must be both spatially and temporally explicit, where form (product) is not considered independently from process (Chorley and Kennedy, 1971; de Boer, 1992; Nanson and Croke, 1992). When applying geomorphology to wetland classification, the first step must be to correctly identify the landform and its spatial extent. Unfortunately, as we have noted, many current wetland classification schemes often confuse and conflate topographic and landform terms, e.g. flats vs. floodplains (Semeniuk and Semeniuk, 1995), use topography to define landforms, e.g. plain vs. floodplain (Semeniuk and

Semeniuk, 2011), or do not consider the range of landforms present in a wetland, e.g. floodplain wetlands with no landform designations (Ollis et al., 2015). The different wetlands discussed in this paper all rely in some way on the presence of a channel; however, the presence and nature of the floodplain is highly variable, and in many cases, the absence of a channel is characteristic of a significant change in wetland structure. For example, the Tshwane and Klip rivers and the Macquarie Marshes, Gwydir and Lachlan rivers are all associated with floodplain wetlands, but the Tshwane and Klip rivers are characterized by single, laterally migrating, through-going channels while the Macquarie, Gwydir, and Lachlan rivers are characterized by multiple channels (anabranches and/or distributaries) that are less laterally active and may undergo breakdown to form floodouts. Moreover, temporal changes in sediment connectivity and landform sensitivity have transformed the Blood River floodplain wetlands within the past century into channeled and unchanneled types (Tooth et al., 2014). Recognition of this spatiotemporal process variability across channel-related wetland landscapes leads to a second step in applying geomorphology to wetland classification, namely to characterize the geomorphological processes and timescales that operate across different wetland landforms.

Both wetland classification schemes (developed primarily by ecology) and riverine classification schemes (developed primarily by geomorphology) have adopted a hierarchal approach (cf. Frissell et al., 1986; Dollar et al., 2007). In ecological wetland classification – e.g. using an HGM approach (Semeniuk and Semeniuk, 1995, 2011; Smith et al., 1995) – a 'top-down' approach seeks to contextualize the wetland by narrowing down the wetland type through stages of progressively smaller-scaled, conceptual levels (Figure 3A) (Sieben et al., 2018). In geomorphological riverine classification – e.g. using the River Styles Framework (Brierley and Fryirs, 2005) – a hierarchy is established by organizing larger-scaled controls, usually starting at the catchment scale, over progressively smaller-scaled features (Fryirs et al., 2018). Crucially, geomorphological hierarchies, like geomorphological concepts, are bidirectional. While larger-scale controls influence the dynamics of smaller-scaled features, smaller-scaled features are, in turn, the 'building blocks' that influence processes over larger spatiotemporal scales (Figure 3B) (Werner, 2003; Thoms et al., 2007; Fryirs et al., 2018). For example, catchment-scale sediment connectivity is dependent on connectivity between landscape compartments and individual channel reaches, and while connectivity potential may be established, sediment transfer is dependent on sediment availability from individual landforms throughout the catchment (Fryirs, 2013; Lisenby and Fryirs, 2017). Moreover, as all geomorphological adjustments represent exchanges of sediment, small-scale sediment connectivity bears significant control over landform morphology and sensitivity at larger scales (Figure 3B) (Harvey, 2001; Wohl, 2017). By contrast, recognition and incorporation of bidirectionality is less evident in ecological wetland classification hierarchies. Bottom-up approaches that account for small-scale features are beginning to be applied to wetland classification schemes (Sieben et al., 2018) where field vegetation data is collected and statistically analyzed to group wetland types (e.g. Sieben et al., 2014). However, this is still a static snapshot and does not impart any consideration of time and process (i.e. dynamism) in the wetland classification.

Ultimately, wetland classification schemes must be as dynamic as the landforms they describe. This implies some combination of ecological and geomorphological characterization is necessary to capture the variability of, and complex interactions between the landforms, hydrology, vegetation, and wider ecology across a wetland landscape (e.g. Phillips, 1995; Walker et al., 1995; Dollar et al., 2007). Applying information on geomorphological processes to reinforce existing ecological wetland classifications is a foundational step in creating more robust wetland classifications. Therefore, the HGM unit can be contextualized through a top-down hierarchy but then redefined according to the capacity for landform adjustment, as characterized through a bottom-up (temporal) approach (Figure 3). This process-landform classification would allow scientists and wetland managers to gain an understanding of not only wetland distribution and type but also the potential for wetland adjustment or change over time. This can be a powerful tool for managers tasked with addressing wetland degradation, where landform adjustments that are different to the expected, natural capacity for adjustment will stand out as anomalous and can be targeted for intervention (cf. Brierley and Fryirs, 2005; Wohl, 2011; Lisenby and Fryirs, 2016).

5. Implications for Wetland Management and Ecosystem Service Delivery

Effective management of wetlands is predicated upon understanding how a suite of biological, ecological, hydrological, geomorphological, and anthropogenic factors interact to develop, maintain, and adjust wetland structure and function (cf. Thoms and Sheldon, 2002). Existing wetland classification tools underutilize geomorphology, so that managers who rely on them may develop an incomplete set of expectations regarding the characteristic processes, forms and timescales of wetland dynamics (McCarthy et al., 2010; Blackwell and Pilgrim, 2011). This may be especially problematic where this dynamism occurs on 'management-relevant' timescales of years to several decades (Ramsar Convention on Wetlands, 2018).

Incorporation of geomorphological perspectives into management planning and practice is important for three main reasons. First, such perspectives can improve understanding of the relative importance of natural and anthropogenic drivers of wetland change, and thus help to decide when – and when not – to intervene. For example, wetland surface incision is not always human-induced (e.g. if resulting from hydroclimatic or threshold slope drivers), nor is short-term incision necessarily detrimental to longer term wetland function (cf. Pulley et al., 2018). In some wetlands, such as those characteristic of northeastern South Africa, bank erosion and incision is an integral component of lateral migration (Tooth et al., 2002), avulsion (Larkin et al., 2017b), and the development of reforming channels downstream of floodouts (Tooth et al., 2014). These processes are essential for redistributing water, sediment, and nutrients across different portions of the wetland over the timescales associated with those forms of geomorphological adjustment (Figure 2). In these and other wetlands, these redistributions will yield coincident changes in wetland ecology (McCarthy et al., 2010; Ralph et al., 2011). In multi-channeled floodplain wetlands such as the Macquarie Marshes, Australia, geomorphological processes also govern the spatial arrangement of, and connections between, channels and floodplains, which can differ greatly in terms of their baseline ecosystem processes, e.g. the gross primary productivity of phytoplankton and planktonic respiration in aquatic habitats (Kobayashi et al., 2013) at landform, reach, and system scales. Geomorphology, not just topography, also determines marginal (edge-water) habitats, which are particularly important for biological function and diversity (Kobayashi et al., 2018). Geomorphological understanding can thus engender management approaches that 'don't fight the site' (Brierley and Fryirs, 2009) but work with the characteristic process-landform relationships operating in any given wetland (Brierley et al., 2013).

Second, geomorphological perspectives are highly relevant in evaluating wetland recovery schemes, which are also termed wetland restoration, rehabilitation or remediation (e.g. Grenfell et al., 2007; McCarthy et al., 2010; Moreno-Mateos et al., 2012). For instance, when aimed at mitigating and/or reversing the detrimental effects of environmental pressures (Figure 3C), managers can use geomorphological knowledge to assess the likely trajectories, rates, and timescales of recovery given the current and possible future states of sediment connectivity and landform sensitivity and their impact on other physical wetland features, e.g. hydrological connectivity (e.g. Balke and Friess, 2016; cf. Calhoun et al., 2017). This is crucial for determining what type of wetland recovery is possible, whether it be reversion toward some pre-impact reference condition or a change to a new state with different structure and function (Kondolf et al., 2006; Moreno-Mateos et al., 2012; Fryirs and Brierley, 2016; Elosegi et al., 2017; Tooth, 2018). Additionally, characterizing landform dynamism within wetlands can be integral to identifying potential barriers to recovery cause by large-scale controls (e.g. climate change) or local anthropogenic impacts (e.g. land management practices) (cf. Elosegi et al., 2017; Ramsar Convention on Wetlands, 2018).

Third, geomorphological perspectives are needed to assess the implications of changing process-landforms relationships for the assemblage and distribution of the associated ecosystem services such as water supply and flow regulation, sediment storage, and biodiversity (Figure 3C). For example, knowing how quickly (or slowly) wetland landforms adjust enables the design and implementation of proactive, adaptive management strategies that may attempt to maintain, enhance or prioritize certain ecosystem services (Rebelo et al., 2015; Tooth, 2018). While the natural capacity for adjustment of wetland landforms is not included as a driver of change in the Millennium Ecosystem Assessment (2005a), sediment connectivity and landform sensitivity need to be considered when assessing the potential for change in wetland ecosystem services resulting from climate or land use disturbances that impact on water-sediment-ecology interactions (Grenfell et al., 2009; Alexander et al., 2015; Tooth, 2018). This is especially relevant to biotic diversity as it relates to landform heterogeneity and ultimately hydraulic and habitat diversity (Poff and Ward, 1990; Benda et al., 2004). While geomorphic heterogeneity does not always correspond to habitat complexity, landform dynamism is a fundamental control over the arrangement of habitat mosaics and the interaction of habitat patches at different spatiotemporal scales (Poole, 2002; Stanford et al., 2005; Wohl, 2016).

6. Conclusions

When viewing a lowland river corridor, an ecologist may see a suite of wetland vegetation assemblages while a geomorphologist may see an assemblage of floodplain process-landform interactions. When viewing a degrading ciénega, an ecologist may perceive vegetation communities at risk from desiccation while a geomorphologist may perceive a valley bottom fill undergoing gully incision. These differences in perspective and focus have metastasized in the wetland research literature with the result that wetland characterization is driven primarily by ecologists and largely ignored by geomorphologists, who instead often see wetlands as part of the river continuum. We highlight this issue because it leads to misrepresentation and underrepresentation of geomorphology in wetland research, with topographic description commonly confused with landform identification, and with such description or identification rarely being linked with the geomorphological processes of landform adjustment that are the essence of many wetlands. Drawing a distinction between product geomorphology (landform) and process geomorphology is a false dichotomy, for landforms are inextricably linked to the processes that adjust them, as we have demonstrated for many riverine wetlands across the drylands of southern Africa, southeast Australia, and the American Southwest. Crucially, many of these adjustments occur on ‘management-relevant’ timescales of years to several decades and so geomorphological perspectives are needed to better inform wetland management planning and practice.

Geomorphological river classification hierarchies are aligned with, and primed for incorporation into, existing ecological wetland classification schemes. Challenges remain in communicating this knowledge across traditional academic disciplinary boundaries and to wetland practitioners; however, overcoming these challenges will enhance wetland characterizations and classifications by helping to account for the dynamism of wetland landforms and the interplay between geomorphology and ecological, biological, hydrological, and anthropogenic factors. In a world where an increasing number of wetlands are being proactively managed to preserve, enhance, or prioritize ecosystem services (Sieben et al., 2011; Rebelo et al., 2015), understanding and accounting for geomorphological process-landform interactions will be critical for establishing expectations of wetland adjustment and associated changes to ecosystem service delivery.

Acknowledgements

During the preparation of this manuscript Peyton Lisenby was an Honorary Postdoctoral Associate of Macquarie University, and supported at Aberystwyth University as a Rutherford Fellow by a Rutherford Fund Strategic Partnership Grant (RF-2018-53) allocated by the Department for Business, Energy and Industrial Strategy (BEIS) and managed by Universities UK International (UUKi). We thank Simon Hunter for pictures of the Gwydir and Lachlan wetlands. We also thank the two anonymous reviewers and the Associate Editor (Sergi Sabater) for comments and suggestions that helped to improve the clarity of this manuscript.

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Figure Captions

Figure 1. Fluvial wetland landforms in selected WiDs. A) Tshwane River, South Africa; B) Klip River, South Africa; C) Blood River, South Africa; D) Okavango Panhandle, Botswana; E) Okavango Fan, Botswana; F) Macquarie Marshes, NSW, Australia; G) Gwydir River, NSW, Australia; H) Lachlan River, NSW, Australia; I) Heradia Ciénega (extinct), Sonora, Mexico; J) Canelo Hills Ciénega (extant), Arizona, USA. Note that scale bars in oblique aerial images are approximate, and mainly indicate foreground scale.

Figure 2. Relationship between forms of geomorphological adjustment, rates and timescales of adjustment, and the landforms produced for different WiDs. Discharges represent the range of bankfull channel discharges. In many cases, discharges are highest at the upstream end of the wetland and decline downstream, and in some cases, disappear at floodouts. Note that specific rates of adjustment in the Lachlan and Gwydir wetlands are not available but are considered similar to those in the Macquarie Marshes.

Figure 3. Illustration of the parallelism between ecological and geomorphological classification hierarchies, indicating where geomorphological process information can be fed into existing ecological wetland classifications. Green-dashed lines represent the interplay that characterizes how geomorphology can influence ecological factors (e.g. influencing HGM unit, soils, vegetation) and how ecology can influence geomorphological factors (e.g. vegetation controlling channel morphology or rates of adjustment). Red-dashed lines represent the interaction of environmental pressures with wetland ecology and geomorphology and the effects that wetland ecology, geomorphology, and environmental pressures can have on ecosystem delivery. Original figure, based on Sieben et al. (2018), Fryirs et al. (2018), and the Millennium Ecosystem Assessment (2005c).

Geomorphological Term	Description
adjustment	The morphological alteration of a landform(s) involving the loss, gain, or redistribution of sediment.
aggradation	A vertical adjustment involving the spatially continuous raising, via sediment deposition, of either: 1) a river channel bed, i.e. *channel aggradation*, or 2) a floodplain surface, i.e. *floodplain aggradation.*
anabranches	Secondary channels that divide from, but ultimately rejoin, the main channel around bars and islands. Channel pattern may be termed anastomosing for organic or fine-grained (mud to fine sand) systems (see *anastomosis*) or anabranching for coarse-grained (medium sand to gravel) systems (Fig 1D).
anastomosis	The process by which a main channel develops multiple, secondary channels (see *anabranches*) that divide and rejoin the main channel around bars and islands. Channels may be termed anastomosing channels (Fig. 1D), and are a fine-grained (mud to fine sand) subset of the broader category of anabranching. Anastomosis commonly involves channel avulsion (see *avulsion*), but in instances where the old channel is not abandoned.
avulsion	The process of formation of a new channel on a floodplain, sometimes leading to abandonment of the old channel (see *paleochannel*).
backswamp	Topographically low portion of the floodplain that remains saturated for extended lengths of time and is often isolated from the river channel as a result of aggradation (see *aggradation*) occurring elsewhere on the floodplain.
channel breakdown	The process by which a river channel loses defined banks over some river length, commonly involving channel bed aggradation (see *aggradation*) and in many instances resulting in the formation of a floodout (see *floodout*) (Fig. 1C, G, I, J).
channel levee	Raised ridge of sediment along the top of a channel bank, formed by sediment deposition during overbank flow (Fig 1B).
cut bank	A landform created via erosion on the outer bank of a meander bend.
distributaries	Secondary channels that divide from but do not rejoin the main channel, often termed 'distributary channels' (Fig 1E).
floodout	A site at a downstream end of a river where channelized flow ceases and floodwaters spill across adjacent, unchanneled, alluvial surfaces (Figs 1C, I, J).
gully	An incipient channel commonly incising (see *incision*) into a floodplain and propagating upvalley via headcutting (see *headcutting*) (Figs 1A, C, I).
headcutting	A directional component of gully or channel incision (see *incision, gully*) indicating the up-valley propagation of incipient channels (see *knickpoint*).
incision	A vertical adjustment involving either 1) the spatially continuous lowering, via erosion, of an existing river channel bed, i.e. *channel incision*, or 2) incipient channels eroding into a floodplain, i.e. *floodplain incision* (see *gully*) (Fig. 1F).
knickpoint	Either: 1) the upstream point of a gully, marked by a vertical or near-vertical scarp located between a channelized downvalley area and an unchannelized upvalley area; or 2) a vertical or near-vertical scarp in the bed of a river channel. Knickpoints propagate upstream in either case and are often termed headcuts (see *headcutting*).
lateral migration	A lateral adjustment involving the sideways movement of a river channel across its floodplain, usually combining erosion of the outer banks (see *cut bank*) and deposition on the inner banks (see *point bar, scroll bar*) to result in the development of meander bends and meander cutoffs (see *oxbow*)

oxbow	Abandoned meander bend now cut off from the main channel via lateral channel migration (see *lateral migration*). Commonly contains standing water for some period of time (Fig. 1B).
paleochannel	An abandoned channel that now forms part of the floodplain, commonly formed via avulsion (see *avulsion*) (Fig. 1A).
point bar	A landform created via sediment deposition on the inside of a meander bend.
scroll bar	A series of former point bars (see *point bar*) that are now part of the floodplain, formed via successive point bar deposition during lateral channel migration (see *lateral migration*) (Fig. 1B, D).

Table 1. Generalized descriptions of geomorphological terms used in this paper

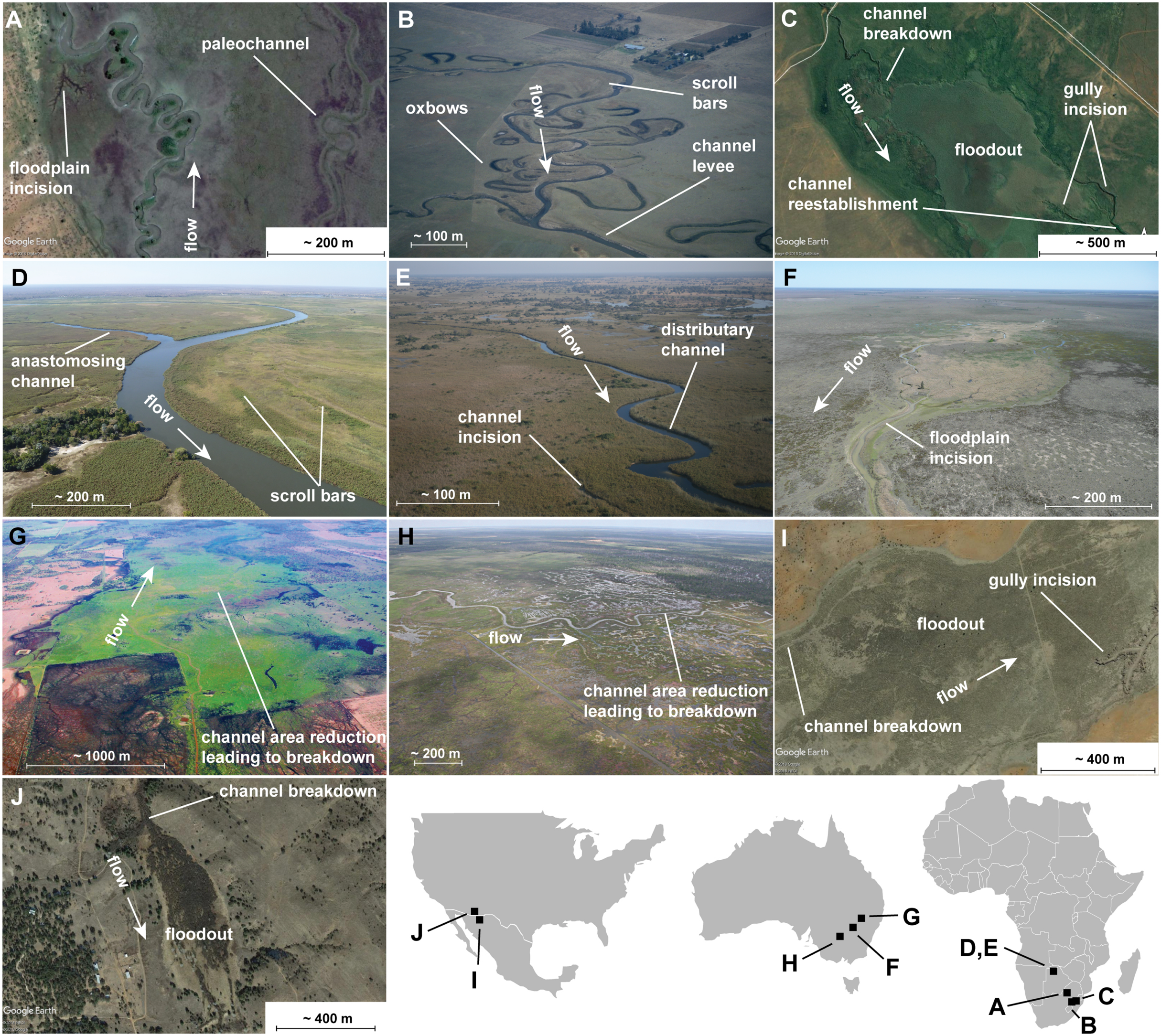
A
paleochannel
floodplain incision
flow
Google Earth
~ 200 m
B
scroll bars
oxbows
flow
channel levee
~ 100 m
C
channel breakdown
flow
gully incision
floodout
channel reestablishment
Google Earth
~ 500 m
D
anastomosing channel
flow
scroll bars
~ 200 m
E
flow
distributary channel
channel incision
~ 100 m
F
flow
floodplain incision
~ 200 m
G
flow
channel area reduction leading to breakdown
~ 1000 m
H
flow
channel area reduction leading to breakdown
~ 200 m
I
gully incision
floodout
flow
channel breakdown
Google Earth
~ 400 m
J
channel breakdown
flow
floodout
Google Earth
~ 400 m
J
I
G
H
F
D,E
C
A
B

Figure 1

PROCESS → TIME

wetland *discharge (Q) & sediment load*	lateral channel migration	aggradation	incision	avulsion
Tshwane River *Q = < 15 m^3 s^{-1} mud, sand, minor gravel*[a]	estimated[a] at > 0.2 m a^{-1}	paleochannel[b] ~ 3.0 - 7.4 mm a^{-1} levees[b] ~ 11.5 mm a^{-1} channel[b] ~ 7.5 - 11 mm a^{-1}	gully headcut migration[b] ~ 76 - 152 m a^{-1}	decadal[b]
Klip River *Q = 10-90 m^3 s^{-1} mud, sand, minor gravel*[a]	[c] < 0.2 m a^{-1}	channel[d] estimated at < 1 mm a^{-1}	gully headcut migration[c] ~ 20 - 70 m a^{-1}	millennial[d]
Blood River *Q = < 15 m^3 s^{-1} mud, sand, minor gravel*[a]	downstream of floodout ~ 0.2 m a^{-1} to 0.0 m a^{-1} over the past 100 years[e]	floodout over the past 100 years[e] > 20 mm a^{-1}	floodout headcut retreat[e] > 25 cm a^{-1}	*not available*
Okavango Delta *Q = 10 - 198 m^3 s^{-1} fine-med. sand*[f]	Okavango (Panhandle) estimated[f] at < 0.5 m a^{-1}	Fan distributary channels[g] ~ 1 - 5 cm a^{-1}	coincident with channel avulsion[h]	decadal-centennial[h]
Macquarie Marshes *Q = 10 - 60 m^3 s^{-1} mud, sand, minor gravel*[i, k]	*not available*	floodplain[i] ~ 0.32 - 0.37 mm a^{-1} floodout[i] ~ 4.09 - 5.56 mm a^{-1}	gully retreat[j] ~ 0.73 - 6.5 m a^{-1} gully incision[j] ≤ 0.32 m a^{-1} gully widening[j] ≤ 0.95 m a^{-1}	decadal[k]
ciénegas *Q = up to 500 m^3 s^{-1} mud - gravel*[l, m]	*not applicable*	ciénega surface[m] up to 1 cm a^{-1}	arroyo headcut migration[n] periodic & highly variable, can exceed 100 m a^{-1} arroyo incision & expansion[n] periodic & highly variable, can exceed 1 m a^{-1}	*not applicable*

PRODUCT → FORM

erosional	channel cut bank		arroyos, gullies, channels	channels
mix	floodplain scroll bars oxbows			paleochannels
depositional	point bars	floodplain, levees, floodouts, fans, deltas		

[a] Tooth 2018 [b] Larkin et al 2017 [c] Tooth et al 2009 [d] Tooth et al 2007 [e] Tooth et al 2014 [f] Tooth and McCarthy 2004
[g] McCarthy et al 1992 [h] Ellery et al 1993 [i] Ralph et al 2011 [j] Oyston et al 2014 [k] Ralph et al 2016
[l] Dong et al 2016 [m] Minckley and Brunelle 2007 [n] Antevs 1952

Figure 2

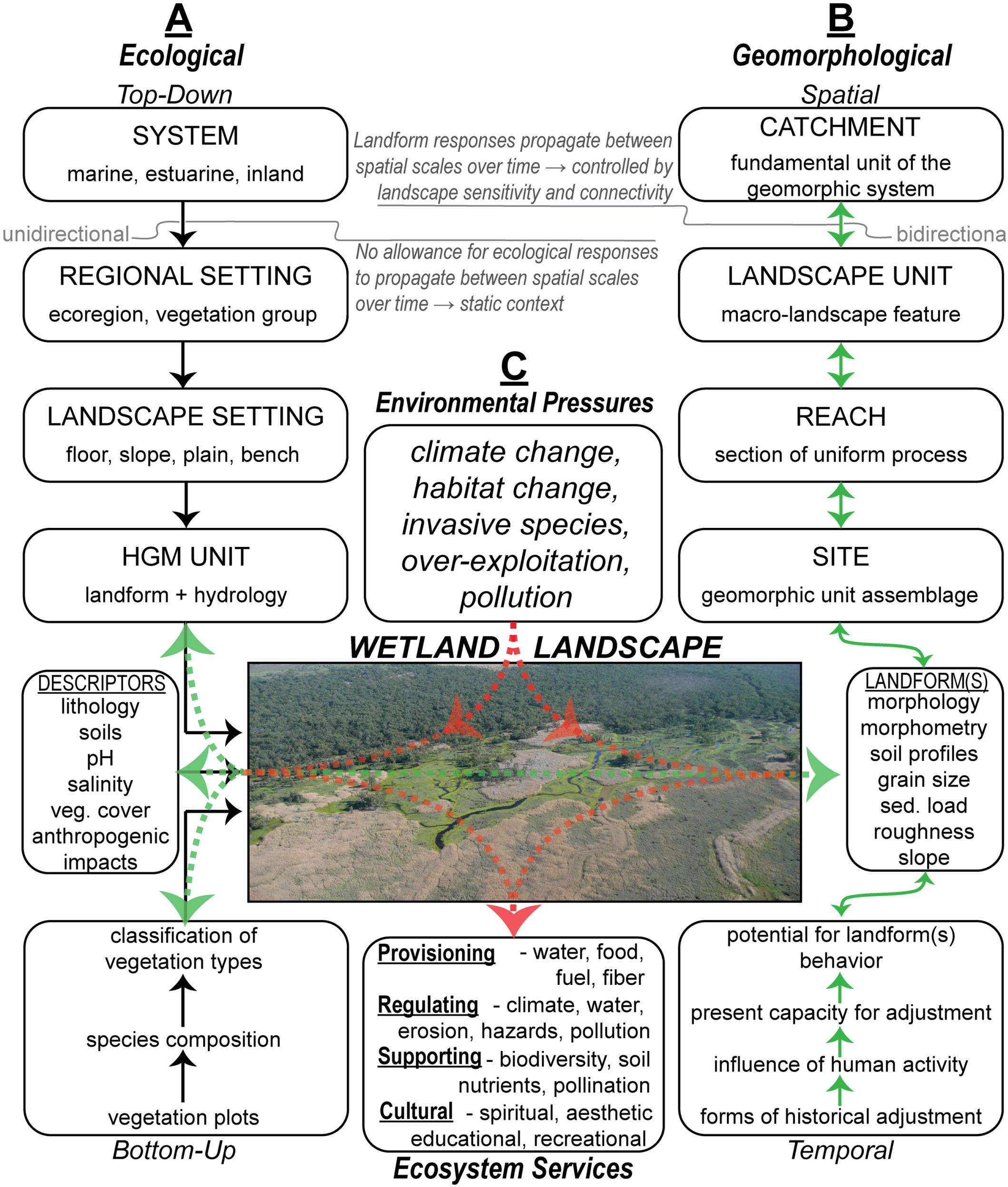
A
Ecological
Top-Down
SYSTEM
marine, estuarine, inland
unidirectional
REGIONAL SETTING
ecoregion, vegetation group
LANDSCAPE SETTING
floor, slope, plain, bench
HGM UNIT
landform + hydrology
Landform responses propagate between spatial scales over time → controlled by landscape sensitivity and connectivity
No allowance for ecological responses to propagate between spatial scales over time → static context
B
Geomorphological
Spatial
CATCHMENT
fundamental unit of the geomorphic system
bidirectional
LANDSCAPE UNIT
macro-landscape feature
REACH
section of uniform process
SITE
geomorphic unit assemblage
C
Environmental Pressures
climate change, habitat change, invasive species, over-exploitation, pollution
WETLAND LANDSCAPE
DESCRIPTORS
lithology
soils
pH
salinity
veg. cover
anthropogenic impacts
LANDFORM(S)
morphology
morphometry
soil profiles
grain size
sed. load
roughness
slope
classification of vegetation types
species composition
vegetation plots
Bottom-Up
Provisioning - water, food, fuel, fiber
Regulating - climate, water, erosion, hazards, pollution
Supporting - biodiversity, soil nutrients, pollination
Cultural - spiritual, aesthetic educational, recreational
Ecosystem Services
potential for landform(s) behavior
present capacity for adjustment
influence of human activity
forms of historical adjustment
Temporal

Figure 3